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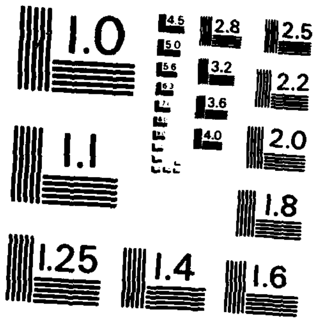

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N. POLLOCK (ARL)

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AERODYNAMIC TEST FACILITY REQUIREMENTS FOR DEFENCE R&D TO 2000 AND BEYOND

by

N. POLLOCK (ARL)
and
M.L. ROBINSON (WSRL)

SUMMARY

Existing Australian aerodynamic test facilities are reviewed with respect to their suitability to meet current and projected Defence needs. The deficiencies of the existing facilities are identified and new facilities proposed.

This document is a compilation of views of the authors and of senior staff engaged in the management and practice of aerodynamics at the Aeronautical Research Laboratories and the Weapons Systems Research Laboratory.

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CONTENTS

EXECUTIVE SUMMARY

This paper has been prepared as part of a response to ASTEC's recommendation on extending and upgrading R&D facilities in aeronautics and aerospace. Following a brief summary of defence needs in aerodynamics, which are considered in more detail in a companion paper, existing Australian aerodynamic test facilities are reviewed, their deficiencies identified and new facilities proposed.

All present wind tunnels in the subsonic, transonic and supersonic speed ranges are found to have major deficiencies which render them inadequate for the defence work currently required or likely to arise in the next few decades. None of the facilities can be economically upgraded and therefore new facilities are proposed.

Current deficiencies are felt most acutely in the transonic speed range where the existing facilities cannot produce reliable test data over an important part of the operational envelope of current combat aircraft. This produces unacceptable uncertainties in store carriage and release tests which could have catastrophic consequences in flight. In addition, mathematical models of aircraft have resulting uncertainties in their aerodynamic data banks which cast doubt on their validity. A new transonic wind tunnel is proposed to overcome these deficiencies. Such a tunnel is estimated to have a total cost comparable to one current combat aircraft.

The present low speed tunnel lacks any viable capability for helicopter or VSTOL aircraft testing and has insufficient productivity potential to adequately service an active local aircraft industry. Since helicopter and VSTOL aircraft usage is almost certain to increase and in the national interest local industry should be encouraged to design and produce aircraft, a dual purpose low speed tunnel suitable for VSTOL and conventional testing is proposed.

The current supersonic tunnels are inadequate for testing aircraft or representative weapon configurations. Up to the present time the demand for such tests has been relatively low. However, effort is being applied overseas to develop aircraft with a realistic supersonic cruise, combat and store release capability. If such aircraft were acquired by Australia adequate supersonic test facilities would be required to support their operation. Capable supersonic facilities are also a prerequisite for local missile development programs. A supersonic tunnel is proposed to meet the needs of foreseen aircraft and weapons testing.

Consideration is also given to ways in which a number of the above requirements could be met by a single new facility.

With the exception of the Woomera Range, Australia's flight test facilities are adequate to handle the current and future workload. However, the decline of the Woomera Range as a facility for aerodynamic and weapons testing gives cause for concern.

Computational fluid dynamics is rapidly growing in importance and is a field which complements wind tunnel testing. Although not strictly within the terms of reference of this paper it is considered that the provision of a large computer capable of running the latest fluid dynamic codes must rank in importance with the provision of new wind tunnels.

1. INTRODUCTION

A large proportion of R&D in aeronautics and aerospace in Australia is undertaken in support of military aviation and weapons systems for the Defence Force. Following its review of science and technology, the Australian Science and Technology Council (ASTEC) reported[1] that the present pattern of R&D in aeronautics and aerospace is a sensible one. However, it observed that basic facilities for this work are now becoming obsolete, and that it is necessary to plan the investment to maintain and extend the capability to support a satisfactory level of R&D.

Defence related R&D in aeronautics is undertaken by the R&D Laboratories of the Department of Defence Support which were until May 1982 part of the Defence Science and Technology Organisation (DSTO) within the Department of Defence. Accordingly, ASTEC recommended to the Prime Minister that the Department of Defence be asked to develop a detailed long term plan for upgrading and extending facilities for R&D in aeronautics and aerospace. The Government agreed to this recommendation and the responsibility for executing the requirements was vested with the Chief Defence Scientist. In October 1980, he asked the Chief Superintendent, Aeronautical Research Laboratories (ARL) to take the lead in developing the plan.

Consideration of facilities for R&D over the whole field of aeronautics and aerospace including the classical areas of aerodynamics, structures, materials, propulsion and systems is required. However in this paper attention is focused on aerodynamics because the wind tunnels necessary for aerodynamics R&D have been in use for many years, and there is a widely held view that existing wind tunnels are inadequate and are becoming obsolete. This view was strongly expressed by the Independent External Review of DSTO[2] as well as by ASTEC[1]. An additional reason for choosing aerodynamics for early consideration in response to ASTEC's recommendation is that wind tunnels are costly and complex items with long lead times for implementation.

A preliminary discussion paper on the subject of upgrading DSTO wind tunnels was circulated to the aeronautical community in November 1980 and many responses supporting the need for attention to this issue have been received. To allow interested parties to express their views, it is planned to hold a workshop on experimental facilities during 1982. The present paper is the second of a series to be prepared for discussion and as a background for the workshop. The first paper entitled, "An Assessment of Australian Defence R&D Needs in Aerodynamics to 2000"[3], identified, in general terms, the work required in aerodynamics for defence needs over the next two decades. In this paper, existing experimental aerodynamic test facilities are reviewed with respect to current and projected defence needs, deficiencies in testing capability identified and the necessary improved facilities specified.

The assessment of defence needs presented in the previous paper was limited to the next two decades because it was considered that projections into the next century were too uncertain. It should be noted however that new facilities planned now will operate well beyond the year 2000 and it would be shortsighted to limit the capabilities of such new facilities to only those requirements which can be clearly foreseen now. Indeed it was noted by Antonio Ferri in the discussion reported in Reference 4 that most major wind tunnels are eventually used for tasks which were not taken into account at all when they were designed. It is obvious that any new facilities which are planned for Australia must be based on clearly identified current and future local requirements. However the opportunity to provide greater and more diverse testing capabilities should not be overlooked if the incremental cost is acceptable.

Only major facility requirements are discussed in this paper. It is expected that in the future, as in the past, a number of small experimental facilities will be built to solve particular problems and for research. As an arbitrary dividing line between major and minor facility requirements the $1M capital cost suggested by ASTEC[1] for National Facilities is adopted.

The views expressed in this paper, as in the previous companion paper[3], are based on the authors discussions with senior aerodynamics staff at the Aeronautical Research Laboratories (ARL) and the Weapons Systems Research Laboratory (WSRL). Where there is a lack of unanimity as to the relative importance of different facilities and capabilities the authors accept resonsibility for the priorities expressed.

2. DEFENCE NEEDS IN AERODYNAMICS

2.1 Aircraft

In Reference 3 current technological trends in military aviation, weapons, fluid mechanics and aerodynamics are reviewed within the framework provided by the functions and roles of DSTO. The main conclusions of that review which reflect on aerodynamic test facility requirements are summarised below.

Manned aircraft are expected to continue to play a vital role in Australia's defence in the decades ahead. Since, with the exception of the Hercules C-130H, all present RAAF and Army aircraft will reach the current estimated "life of type" before 1995, many new aircraft types will enter the inventory during the life of any aerodynamic test facilities selected now. Many of these aircraft, particularly combat and VSTOL types, will incorporate some of the advanced aerodynamics technology which is currently being developed overseas. Since many of these new aerodynamic developments will require test capabilities which are not currently available in Australia new tunnels are needed. It is essential that a realistic capability to test current and future aircraft in service in this country is maintained for the following reasons:

a. To operate modern combat aircraft efficiently it is necessary to have high quality mathematical models of the aircraft performance and handling characteristics. This will become even more vital in the future when aircraft characteristics can be fundamentally altered by simple changes to the software of the flight control computer. An operator who does not maintain a capability to design, assess and implement such changes will be at a basic operational disadvantage. Experience has shown that aircraft manufacturers cannot be relied on to provide the aerodynamic data required by mathematical models. Wind tunnel tests are the basic source of aircraft aerodynamic data and will remain so until well into the next century.

b. Adequate test facilities and the body of aerodynamic expertise which grows around such facilities are necessary for the assessment of new aircraft types. In the absence of an independent test and assessment capability the Department of Defence would be less well equipped to select between competing manufacturers' proposals. It is interesting to note that the Department of Defence of the USA, which has much closer contact with aircraft manufacturers than we have, supports an impressive independent test capability to maintain its position as a "Smart Buyer"[5].

c. The carriage and release of external stores is fundamental to most combat aircraft operations. In practice each combination of aircraft and store must be separately investigated and cleared. The investigation normally includes the effect of the carried store on the aircraft performance, stability and flight envelope, the early post release trajectory in relation to aircraft safety and aiming point accuracy and the effect of the release transient on the aircraft behaviour. Wind tunnel tests are preferred for this work since flight trials are hazardous and expensive.

Operational requirements have often dictated that RAAF aircraft carry and release stores which were not cleared by the aircraft manufacturer, or carry stores in a different way from that for which the stores were cleared. To maintain operational flexibility it appears inevitable that store substitution and carriage changes will continue. An adequate local test capability in this field is therefore of great importance.

d. If local design and development of military aircraft is contemplated, and the present commitment to a local RAAF basic trainer design is a favourable pointer, the existence of adequate test facilities at the start of the program is vitally important. It was noted in Reference 4 that "Data obtained at this early stage of the program has an extremely high leverage on program costs,.....". Basic configuration design errors occurring early in an aircraft project due to inadequate test facilities cost an inordinate amount of money to correct at the flight prototype stage because by then the production tooling is well advanced. Unfortunately, due to the long lead time required for test facility development, by the time an aircraft development has been conceived it is too late to build a wind tunnel which could have an impact on the design. The provision of wind tunnels and other test facilities to support local design must therefore be looked upon as a long term investment in the future. Facilities suitable for the support of aircraft design would in most cases also be well suited for testing remotely piloted vehicles (RPVs), targets and drones.

2.2 Weapons Systems

Of the many weapons systems used by the three Services the majority involve some form of flight vehicle. Even for simple unguided munitions such as bombs and shells the impact point scatter is dependent on the aerodynamic design. For more complex weapons, like precision guided munitions (PGMs) and stand off bombs, the system performance is often dominated by the aerodynamics.

Many weapons systems are now so complex that their behaviour can only be fully appreciated through mathematical modelling. Adequate aerodynamic test facilities are required to provide data for such models. It should be emphasised that testing of munitions in wind tunnels or other laboratory facilities can result in large cost savings. For example, a bomb with an unacceptable impact point scatter due to marginal stability can be studied and improved in a wind tunnel for orders of magnitude lower cost than would be involved in obtaining the same data from flight trials.

Australia has a history of successful local design and development of weapons systems, recent examples being Ikara and Karinga. It seems likely that local design and development of weapons which suit our particular requirements will at least continue and could increase in the future.

The independent assessment capability growing out of the possession and operation of advanced test facilities would also be of value when weapons are purchased overseas.

2.3 Test Facilities

The possession of significant aerodynamic test facilities confers indirectly other advantages which are of real strategic value. Such facilities would appear to potential aggressors as an expression of a national commitment to a continuing vigorous and independent defence posture. This visible commitment could well have a significant deterrent effect.

A valuable contribution to Australias aerodynamic technology base comes through international exchanges and collaboration through The Technical Cooperation Program (TTCP), the Mutual Weapons Data Exchange Agreement (MWDDEA) and the Commonwealth Aeronautical Advisory Research Council (CAARC). The advantage derived from these arrangements is strongly dependent on the level of our input. No cooperative program can survive in the long term if the data flow is seen to be predominantly one way. Enhanced aerodynamic test facilities in Australia would therefore not only maintain our own independent capabilities but also improve our access to overseas information.

It is probable that countries in our region and even some remote from us would wish to use our test facilities if they were of an adequate standard. This could bring considerable economic and political advantage to Australia.

2.4 Relevant speed regimes

From the review of Reference 3 it is possible to draw some conclusions regarding the relative importance of the various flight speed regimes. At the present time, both overseas and in Australia, the major interest is in the high subsonic, transonic and low supersonic ranges. These three speed ranges are normally covered by so called transonic wind tunnels. The importance of this speed range is that it includes the majority of current, and short term projected, military aircraft operations. In addition many weapons such as cruise missiles, free fall bombs and artillery shells operate at these speeds.

All aircraft, whatever their speed potential, must operate efficiently at low speed during take-off and landing. Data on the low speed performance of aircraft will always be required if a capability to study the whole operational envelope is to be maintained. A number of propeller driven aircraft in the Defence inventory, such as the RAAF basic trainer, operate entirely in the low speed area. If as seems probable, VSTOL aircraft come into greater use in the three Services, the importance of the low speed area will significantly increase. In particular, the simulation of the high lift low speed flight of these aircraft requires test capabilities which are not currently available in this country.

At the present time many missiles operate at supersonic speeds, but military aircraft enter this speed range only briefly due to the high rate of fuel usage which results. In the medium to long term future it is possible that military aircraft operations will move increasingly into the supersonic range. Despite the limited current interest, Australia should plan for an adequate supersonic test capability to meet future needs.

The hypersonic speed range is currently of lesser importance to Australian defence. However there are some indications that hypersonic projectiles for armour penetration may be developed in the future. It is therefore recommended that a watch be kept on the field so that Australia is not caught unprepared if appropriate hypersonic projectiles are developed. However, because of the absence of medium term interest, hypersonic facilities will not be considered further in this paper.

3. MAJOR DEFENCE SUPPORT AERODYNAMIC FACILITIES

The R&D Laboratories of the Department of Defence Support have a number of major (by current Australian standards) aerodynamic test facilities which have for many years supported the bulk of defence R&D in aerodynamics. In this section these facilities are described and their deficiencies noted.

3.1 ARL Low Speed Tunnel

Following a report to the Australian Government by H.E. Wimperis in 1937, ARL was established and a 2.7 m x 2.1 m low speed tunnel planned. This tunnel was completed late in 1941 and put into service early in 1942[6]. The prime purpose of the tunnel at that time was to support local military aircraft design. The tunnel is a conventional closed circuit type with a fan drive and an irregular octagonal working section. The contraction ratio is 4:1 and the only flow manipulator in the circuit is a 25 mm cell honeycomb 130 mm long located after the fourth corner.

During its 40 year life the tunnel has been fitted with a number of new fans and the drive power has been increased from 410 kW to 661 kW which has raised the maximum tunnel speed from 86 m/sec to 103m/sec. Being an atmospheric operating pressure facility the available test Reynolds number is directly proportional to the tunnel speed. The maximum Reynolds number (based on the square root of the test section area) is 15×10^6 which corresponds to a typical model chord Reynolds number of 2×10^6. To facilitate comparisons between the various tunnels discussed later, all Reynolds numbers quoted in future are based on the square root of the relevant test section area unless otherwise stated.

The original fixed test section has been replaced with two interchangeable sections to improve tunnel productivity. The tunnel is currently equipped with a four component under floor mechanical balance and a six component internal strain gauge balance. A wide variety of model mounting hardware and model attitude control systems is available. Pressure measurements are handled by up to six, 48 port Scanivalves. A number of special compact, high power electric motors, along with their supply and control systems, are available for powering propellers on models. Hot wire anemometer equipment is available for unsteady velocity measurements and smoke generators are used for general flow visualisation and particularly for funnel and chimney plume investigations.

All the tunnel data are multiplexed down a serial line to the main ARL time sharing DECsystem10 computer system. Computed data are returned to the tunnel control room for print out and display via the same serial line. All data acquisition, data reduction, file manipulation and plotting are carried out on the main site computer system. Models are made of wood and metal in model shops which support the whole ARL complex.

The single largest category of work carried out in the low speed tunnel has been, and still is, force measurements on aircraft and missile models, primarily in support of design and development but also for operational problem solving and data provision for mathematical modelling. Over the last 30 years more than 25 different aircraft and missile types have been tested, many of them involving a number of different models. A significant number of the aircraft tests have also involved the jettisoning of stores and components (e.g. canopies). In addition to this primary workload there has been an extremely diverse selection of other tests carried out for Defence, other Government Departments and for Industry.

A relatively small amount of research on two dimensional aerofoils, elta wing vortex flows and flutter has also been carried out.

In recent years the Low Speed Tunnel annual operating hours have varied etween about 100 and 380 with an average around 250. It should be noted hat test preparation and data analysis takes considerably longer than ctual tunnel operation. In general, low speed tunnel operation has been etermined by the imposed workload and not constrained by tunnel erviceability or staff availability.

The deficiencies of the existing tunnel fall into three categories; flow uality, productivity and testing capability. The test section flow uality in terms of mean flow uniformity, steadiness and turbulence is nown to be deficient by modern standards. Proposals to overcome this roblem by the installation of a wide angle diffuser, screens and a new ontraction are under active consideration. Tunnel productivity is imited by overheating of the tunnel air during high speed operation in hot eather and by inadequate model preparation arrangements. The overheating roblem could be overcome by the installation of adequate cooling, and arious approaches to this are being studied. The model mounting and reparation problems are imposed by the physical space limitations in the uilding housing the low speed tunnel. Studies carried out up to now have ailed to find any fully satisfactory solution to the problem of model reparation. The testing capabilities of the tunnel have been well suited o most of the past and present work, although a higher maximum speed would e of value particularly for jettisoning tests and a larger test section ize would permit improved fidelity of models and more extensive use of ontrol surface actuators. However the tunnel test section size is totally nadequate for VSTOL or rotary wing aircraft tests. Even the use of a entilated test section, assuming this were practical, would not permit ealistic VSTOL testing in the existing tunnel.

Despite its known deficiencies it is considered that the ARL low speed unnel should be retained and upgraded by improving the flow quality and roviding adequate cooling. Improvements to the tunnel instrumentation ncluding the provision of a dedicated mini-computer and the production of ore strain gauge force balances are currently under way. Even with a major ew low speed facility it is considered that the existing tunnel would be ore cost effective for preliminary development testing where the extended apabilities of the new tunnel were not needed. The existing tunnel would so be useful for research, provided the flow quality could be improved ufficiently, since it is notoriously difficult to justify research work in arge tunnels with high operating costs.

3.2 ARL Transonic Tunnel

Shortly after the commissioning of the ARL low speed tunnel in 1942 a further tunnel was planned. This facility, which was referred to as the Variable Pressure Tunnel (VPT), had a relatively small test section and was designed to be pressurised to 650kPa to give low speed test Reynolds numbers similar to the low speed tunnel, and depressurised to about 40kPa to permit tunnel speeds approaching sonic. Following the completion of this tunnel it was found to be underpowered and little useful work was done until 1950 when a Rolls Royce "Merlin" aircraft engine and a new two stage compressor were fitted. A lack of tunnel cooling and operational difficulties with the engines still severely limited tunnel productivity. In 1956 the tunnel was extensively modified and converted to transonic operation. This work involved the installation of a 1650 kW electric drive, new gearbox, new contraction, a slotted test section of increased size, cooling and improved model access. It was intended to fit auxiliary plenum chamber suction, but despite a supporting recommendation by the Commonwealth Advisory Aeronautical Research Committee (CAARC), lack of funds prevented this being done. At that stage the tunnel became a highly productive facility. The final major improvement to the tunnel was in 1961 when a new four stage compressor was installed.

The tunnel as it currently exists is a continuous flow closed circuit type with a test section 530 mm by 810 mm . The tunnel has a cooling radiator and two screens upstream of a 27:1 contraction. The operating stagnation pressure can be varied between about 15 kPa and 200 kPa. To achieve Mach numbers above 0.6 the tunnel pressure must be reduced below atmospheric because of the limited power available. The maximum tunnel test Reynolds number (based on the square root of test section area) falls from about 8.5×10^6 at the minimum practical test Mach number of 0.4 to 2.3×10^6 at a Mach number of 1.4. The minimum useful test Reynolds number is limited only by measuring accuracy problems at very low tunnel pressures.

The tunnel is equipped with a wide selection of multi-component strain gauge balances for force measurements and up to five, 48 port Scanivalves for pressure measurements. A 406 mm aperture optical system equipped for schlieren, shadowgraph and interferometric observations is available. All tunnel data gathering and data reduction are carried out on a dedicated mini computer system. A real time display of selected computed results is available in the tunnel control room. Some complex calculations such as the integration of pressure distributions are carried out on the main site computer. Data transfer between the tunnel and the central computer is by magnetic tape. Model manufacture is carried out by the same model shops that support the low speed tunnel.

The major workload in this tunnel is force measurements on aircraft, bomb and missile models. In the past this work was primarily in support of design and development by local industry but more recently provision of data for mathematical modelling has predominated. Another significant activity has been the calibration of airspeed and direction probes for flight tests. In addition to the work directly relevant to defence described above there has been, at least until recently, an active research effort in the transonic tunnel. This work has included investigations of transonic scaling laws, tunnel wall interference, supercritical aerofoil design, two dimensional base drag and three dimensional separation.

Actual tunnel operation has averaged about 100 hours/year over the past ten years. During the 1960s a peak of 300 hours/year, limited by model preparation and tunnel depressurising time, was achieved. The primary factor producing the low recent utilisation has been lack of available staff and not tunnel unreliability or the absence of workload. A number of existing tasks remain uncompleted and recently new work has been discouraged in an attempt to overcome the backlog.

The most important deficiency of the present tunnel is the low test Reynolds number. For modern fighter aircraft the maximum tunnel test Reynolds number is two orders of magnitude below flight values. The Reynolds number dependence of the aerodynamics of military aircraft configurations and their maximum operational angle of incidence has increased in recent years and the situation has now been reached where extrapolation of ARL transonic tunnel data to flight conditions is often impossible. Even bomb and missile tests pose problems in the extrapolation to flight conditions. It appears that for reasonably confident prediction of flight characteristics at transonic speeds, for present aircraft, a test Reynolds number of at least a quarter of full scale is required[7,8].

The second major disadvantage of the present transonic tunnel is its small test section size. The small models accommodated by this test section are difficult to manufacture to the required accuracy. The resulting long manufacturing time and high cost of models severely restricts tunnel productivity. The model scale also makes it difficult to provide manually adjustable control surfaces and impossible to provide on-board control surface actuators. These restrictions further limit tunnel productivity. Studies of the above problems have failed to produce a satisfactory solution short of acquiring a new larger tunnel.

The ARL transonic tunnel is unsuited to aircraft testing, but satisfactory for testing small bombs and missiles and well suited to research. It is considered that the existing tunnel would provide a valuable research capability for many years at little cost, and should be retained for this purpose even if a new large tunnel were built.

3.3 WSRL Subsonic-Supersonic Tunnel S-1

The S-1 wind tunnel was built during the period 1952 to 1955, and commissioned in 1957 to provide a supersonic aerodynamic test facility in Australia in support of the guided missile testing programme then being conducted at the Woomera Range. The tunnel is powered by a 3 MW variable-speed induction motor driving a modified "Nene" centrifugal compressor. It was designed originally to operate as a variable-pressure supersonic facility in the Mach number range 1.6 to 2.8 with a nominal working section size of 380 mm square. Constraints on power, cooling and pressure limit the maximum Reynolds number at supersonic speeds to 4.6×10^6. Operating stability dictates a minimum Reynolds number limit of 1.5×10^6 in the supersonic speed range.

In the early 1960's, the tunnel speed range was extended downwards to a Mach number of 1.4 by the provision of a suitable nozzle. In 1965, in response to a growing need for aerodynamic testing at subsonic speeds, slotted nozzle liners were designed and fitted to the top and bottom walls of the working section. This enabled the tunnel to operate in the Mach number range from 0.3 to 0.95 without modification to the drive system. Mach number in the subsonic range is controlled by a remotely-operated variable-area diffuser located downstream of the working section. The maximum achievable subsonic Reynolds numbers vary from 4.6×10^6 at a Mach number of 0.5 to 3.0×10^6 at Mach numbers of 0.3 and 0.9.

The tunnel is equipped with a quadrant type pitch and roll mechanism which allows model attitude to be set by remote manual or computer control. An x, y, z and roll traversing unit, which is also under manual or computer control, allows the accurate positioning of probes or model stores. These two positioning mechanisms are vital for store carriage and release testing. Data acquisition, experiment control, data analysis and display of results is carried out by a dedicated PDP UNICHANNEL 15 minicomputer system. Complex or extensive analysis and manipulation of data is carried out off-line using the central IBM 370-3033 computer at DRCS. A comprehensive range of force balances and pressure measuring systems is available. The S-1 tunnel has a 295 mm diameter optical system which can be used for schlieren and shadowgraph flow visualisation.

Wind tunnel models are manufactured in a Model Shop manned by a foreman and several experienced craftsmen. Because traditional model making techniques are used, the manufacture of complex models to the small scales required is time consuming and costly. At present there is no operational numerically-controlled machine tool in the Model Shop, but initiatives are being taken to remedy this deficiency.

Over the past five years the S-1 wind tunnel has averaged between 250 and 300 hours of actual operation per year. The time taken to prepare experiments in the tunnel working section is estimated to be approximately the same as the operating time.

Experiments related to aircraft-store interaction occupy a high proportion (>50%) of tunnel operating time. Aerodynamic project studies such as that concerned with a 500 lb gliding bomb constitute approximately 20% of tunnel time, and the remaining available tunnel time is taken up with aerodynamic research, the consolidation of aerodynamic data banks on weapons, the ad hoc solution of aerodynamic problems for the defence community and the development and assessment of new methods and techniques. It should be noted that tunnel operating hours are more constrained by the limited availability of scientific and operating staff than by unavailability of the tunnel and support equipment through breakdown or maintenance.

Since the S-1 test section dimensions are about 60% those of the ARL transonic tunnel the problems with small model scale discussed with reference to the ARL tunnel apply even more to the S-1 tunnel. The scale problem is made even more acute by the preponderance of store release tests in the tunnel workload. The store release test technique used involves force measurements on a store at a grid of points in the flow field of the parent aeroplane, and for this purpose models of both the aeroplane and store must be present in the working section at the same time. The largest sizes of complete models of the Mirage and F-111C aircraft that can be mounted in the working section are 1/50th and 1/80th scale respectively, but external stores at these scales are too small for a force measurement balance to be fitted. The smallest size of strain gauge balance that can be made and mounted within an external store model dictates that the smallest size of a typical store is 1/24th scale. Even at this normally unacceptable small scale, it is possible to mount only a half-model of the Mirage aircraft or a part-model of the F-111C aircraft in the working section using the reflection plate technique. These models produce an excessive blockage of about 5%, five times the accepted figure for transonic testing.

The S-1 tunnel has a similar test Reynolds number capability to the ARL tunnel in the transonic speed range and the problems discussed in section 3.2 apply equally to both tunnels.

At Mach numbers 1.4 and 1.6 the working section of the tunnel is too small because blockage and shock wave reflection effects place severe limits on the size of models that can be tested. Fortunately, as Mach number increases supersonically the sensitivity of the flow to scale effects decreases and for tests at higher Mach numbers (M>1.8) the tunnel working section may be classed as of minimal size. Provided care is taken in simulating boundary layer development by the use of appropriate tripping devices and provided test results are interpreted with caution, meaningful data can be obtained.

The tunnel also exhibits problems with test section flow temperature uniformity, high vibration levels from rotating machinery, the lack of a test capability in the Mach number range 0.95 to 1.4 and high maintenance costs because of the age of components. Consideration has been given to methods of updating the tunnel in terms of both performance and reliability, to satisfy foreseen needs in the next decade. Wind tunnel S-1 in its present subsonic ($0.2<M<0.95$) mode of operation is inefficient, since the compressor characteristic is poorly matched to tunnel demands. Furthermore, the working section size is far too small, raising doubts about the validity of test data and forcing severe compromises in the conduct of experiments. Accordingly, the feasibility of installing an additional, better-matched and larger working section for subsonic-transonic operation has been examined. Unfortunately, no satisfactory cost-effective solution could be found.

Because of the long history of main electric motor failures, two alternative main drive proposals were investigated; one was a new electric motor and compressor, and the other was an induction drive system based on ejectors driven by a high pressure air supply based on existing storage. The first proposal proved to be very expensive and the second feasible for subsonic-transonic operation, but technically impossible for the supersonic regime. These investigations have led to the conclusion that no further major modifications can be profitably made to the tunnel to extend its performance; it has reached the end of its evolutionary development. If the current level of maintenance is sustained, the tunnel could be expected to perform a useful role in experimental aerodynamics for at least ten years. Beyond this time the obsolete state of the tunnel may render its further use untenable.

3.4 WSRL High Speed Supersonic Tunnel S-3

Tunnel S-3 is a small, supersonic blowdown tunnel which was commissioned in 1957 and has never been fully developed. Assessment of the original regenerator showed that the welding was faulty and that the design was unsuitable for high pressure operation. Subsequently, the tunnel was redesigned and rebuilt at low priority, being recommissioned in 1966. Following its recommissioning, vacuum tanks with a capacity of $250m^3$ have been added and the air circuit has been arranged so that the tunnel can exhaust either to atmosphere or to vacuum tanks. At the same time the high pressure storage capacity has been more than doubled to $7.7m^3$ at a pressure of 8 MPa. Recently, with the dismantling of a missile launcher facility at

Woomera, 2.2 km of high quality steel piping were procured at negligible cost. This piping, having a volume of 49.5m^3 and an original working pressure of 34 MPa, is being installed to provide a very large increase in the high pressure air storage capacity.

In its present form the tunnel working section is 180 mm x 150 mm, and the normal Mach number range is 2.8 to 5.0, with a limited test capability at M = 1.4. The tunnel is designed to operate over the stagnation pressure range from about 100 to 2800 kPa. Taking into account the various present operating constraints of the tunnel, the minimum Reynolds number is 1 x 10^6 and the maximum Reynolds number is 8 x 10^6.

A simple automatic control system maintains the stagnation pressure within 2% of the set value, and a capacitive heat regenerator in the settling chamber controls stagnation temperature within a few degrees Celsius of the mean value.

Two compressors, each powered by 37 kW motors, and one vacuum pump powered by a 19 kW motor, provide the motive power for the tunnel, and permit tunnel runs of up to 60 sec duration at intervals of about 2 hours. Vacuum exhaust is used to minimise model loads during flow establishment and breakdown at high Mach numbers. This is particularly important for avoiding damage to models and balances when starting the tunnel at Mach numbers of 4 and 5.

The tunnel is fitted with a simple motorised incidence change mechanism and model support that is adequate for present purposes but may require renewal in the future. Standard schlieren and shadowgraph optical systems are available. Data acquisition is accomplished using temporary purpose-oriented systems or using the S-1 tunnel data acquisition system. The latter requires data transmission over a distance of 200 m, and further development is necessary to achieve the full potential of the system.

There is no formal work programme for S-3 tunnel, and the facility is not operated on a regular basis. A minimum number of about 50 tunnel runs per year is carried out to exercise the plant and maintain skills in the operation of an intermittent tunnel. Recent work has included a collaborative project on shock wave behaviour with the Physics Department of the Australian National University, the development of a Mach number 1.4 nozzle and development of an improved model support system.

In the next two or three decades there is likely to be greater emphasis on missile aerodynamics in the high supersonic speed range and it is believed that the Mach 5 capability of tunnel S-3 will become very useful. High speed missiles are likely to manoeuvre only at low angles of incidence, and although the tunnel working section is small, it should be possible to test small models at relatively high Reynolds numbers because of the high unit Reynolds number capability of the tunnel. Size-related problems of blockage, test diamond limitations and shock wave reflection are alleviated at the high Mach numbers for which S-3 tunnel is designed.

It is worth pointing out that the highest Reynolds number is achieved by operating the tunnel at a maximum stagnation pressure of 2.8 MPa. Operating under these conditions may impose very high loads on the model and its support during the tunnel starting and stopping processes, and during tests the high dynamic pressure (typically 50 times that in tunnel S-1) limits the type of experiment that can be conducted. Notwithstanding these difficulties, tunnel S-3 has a very useful Reynolds number range and can provide worthwhile data which should be reasonably representative of missile flight conditions at high Mach numbers. This observation follows from the decreasing sensitivity to scale effects as Mach number increases, combined with the ability to determine trends in data by conducting tests over a considerable Reynolds number range.

It is concluded that despite the small test section size and the undeveloped state of the tunnel, it has good potential to contribute in the future to missile aerodynamic research at high Mach numbers.

3.5 Gun Launched Vehicle Range

WSRL has developed an outdoor aeroballistic range facility to investigate the flight dynamic behaviour of unguided weapon configurations. Two guns are available, a 127 mm calibre gun located at the Proof and Experimental Establishment at Port Wakefield, S.A., and a 384 mm calibre gun located close to the laboratories of Aeroballistics Division (AD), WSRL at Salisbury, S.A. The current interest in gas guns began in 1967 during investigation of the flight behaviour of self-dispersing bomblets. It was found that gas gun firings of bomblets singly and in clusters provided a cheap and effective method of assessing flight behaviour.

The gas guns enable a large variety of flight vehicles ranging from small bomblets with a mass of 0.5 kg to large fin-stabilised vehicles with a mass of 50 kg to be launched at speeds up to 200 m/s. Recognising the importance of the transonic speed regime, a 265 mm calibre gas gun with a transonic launch capability has been constructed and is being installed at Port Wakefield.

Data on flight behaviour are obtained by the following methods:

a. telemetry systems which record the output of motion sensors on the flight vehicle;

b. ballistic cameras which photograph flashing lights carried in the flight vehicles; analysis of photographic records gives precise trajectory and motion data from which aerodynamic data are derived;

c. cine cameras which provide qualitative photographic records of initial flight behaviour.

To date, the ballistic camera technique has been most used for quantitative analysis of flight behaviour. Using parameter estimation methods of analysis on the DRCS central computer, static and dynamic aerodynamic derivatives can be calculated from the trajectory data. Aerodynamic data that are currently obtained include axial force, normal force derivative, pitching moment derivative, pitch damping moment derivative, and Magnus moment derivative.

Although not used intensively at present the 127 mm and 384 mm gas guns provide an invaluable facility for carrying out ad hoc aerodynamic tests on a variety of weapons. The smaller gun is used currently to assess the dispersing performance of production-standard Karinga bomblets. The 384 mm gun has been extensively used for quantitative measurements of the flight dynamic behaviour of bomblets, Mk 82 bomb shapes and projectiles with folding fins. It is also used for dispersion tests on clusters of bomblets. The commissioning of the 265 mm gas gun will provide a transonic launching facility enabling high speed aerodynamic experiments to be carried out in an unconstrained environment. The gas gun launched vehicle technique is an economical method of carrying out aerodynamic research and ad hoc studies of weapons, and for validating wind tunnel tests over a limited speed range.

3.6 Rocket Launched Vehicle Range

The Range at Woomera has been progressively run down from its previous high standard to a level at which successful trials cannot consistently be conducted. The instrumentation systems are incomplete, staff lack experience in operating the available systems and realistic training aids no longer exist. In addition, support services such as workshops and stores have been withdrawn from the rangehead.

The present situation is such that serious consideration must be given to alternative methods of gathering the required data rather than use the Range with its present inadequacies. The mounting of a trial at the Woomera Range is a very costly and time-consuming exercise because most of the support, both staff and equipment, must be provided from DRCS at Salisbury, S.A.

As a result the Range is sparingly used for aerodynamic investigations; For example, WSRL has carried out only two such experiments at Woomera in two years. During 1982-87 increased use of the range is planned. In the aerodynamics field current plans include up to eighteen rocket-launched vehicle trials and up to eight air-dropped vehicle trials, all of these requiring a well instrumented facility.

3.7 Computers

Although not strictly aerodynamic facilities, digital computers and computational aerodynamics fill a similar role to wind tunnels. In a wind tunnel the flow of air about an aircraft or weapon model gives a precise analog representation of the flow pertaining to the test conditions (which usually do not fully represent full scale flight conditions). In the computational approach a numerical representation of the aircraft or missile is used and the equations of motion are solved with varying degrees of approximation on a computer. Recent rapid computational advances have raised questions regarding the future role of wind tunnels for aerodynamic testing. However the extensive review of Reference 12 concluded that "For the foreseeable future computers and wind tunnels will be complementary".

Both ARL and WSRL have general purpose time sharing computer systems which are completely inadequate for running programs currently available through the NASA Computer Software Management and Information Centre (COSMIC). Limited access to the CSIRO computer in Canberra is available but this machine is inadequate for the fluid mechanics codes now becoming available. Although detailed recommendations are beyond the scope of this paper it appears highly desirable that a large computer capable of running the latest fluid dynamics codes should be available to the Defence R&D community. Such a facility ranks in importance with adequate wind tunnels.

4. SIGNIFICANT NON-DEFENCE SUPPORT FACILITIES

There are a small number of aerodynamic facilities not under the control of the Department of Defence Support which make, or have the potential to make, a significant contribution to Australia's Defence R&D. These will be briefly reviewed.

4.1 Other Wind Tunnels

Most Australian Universities and Institutes of Technology possess wind tunnels. A few of the low speed tunnels have test section sizes and speed capabilities which make them potentially suitable for some aircraft testing. However these tunnels are instrumented for their normal research workload and do not have the model support and attitude control hardware, multi component force balances and data reduction hardware and software required for aircraft and weapons testing. Taking an overall view it is evident that the low speed wind tunnels in academic institutions are less suitable for aircraft model testing than the ARL Low Speed Tunnel. However for tests where very high flow quality or a simulation of the natural wind is required the tunnels in some institutions significantly exceed the capabilities available in the R&D Laboratories.

There are also a small number of low speed tunnels in CSIRO and in industry. It is not considered that any of these facilities extend the capabilities available in the Laboratories and academic institutions.

All the transonic and supersonic tunnels outside the Laboratories are small demonstration and research facilities with little capability for aircraft or missile testing.

Where tunnels outside the Laboratories are more suitable for a particular Defence problem than those available within, it would appear sensible to have the work done under contract in the most appropriate facility, security requirements permitting.

4.2 RAAF Aircraft Research and Development Unit

For many years the RAAF has maintained an Aircraft Research and Development Unit (ARDU) located initially at Laverton Victoria and now at Edinburgh South Australia. The main role of this unit is conducting flight tests on RAAF aircraft and stores to solve current problems, but flight tests for Army, Navy and the R&D Laboratories are also carried out.

Traditionally the major workload of ARDU has consisted of aircraft performance determination in a tropical atmosphere (which is significantly different from the standard atmosphere in which performance is usually specified), the clearance of stores for carriage and release , the solution of operational problems and the certification of modifications to RAAF aircraft. Recently a significant amount of test flying has been devoted to providing data for the verification of aircraft mathematical models and wind tunnel test results, and more tests of this type are planned.

In the recent F/A-18 aircraft purchase for the RAAF, provision was made to acquire two specially instrumented aircraft from the manufacturer for operation by ARDU. For the F-111C where an instrumented aircraft was not purchased, considerable local effort has been expended on designing and constructing a suitable instrumentation package, and when the original instrumented Mirage IIIO aircraft was lost in a flight test accident a second instrumented aircraft was purchased. These examples illustrate the importance that is attached to having instrumented flight test aircraft available.

The flight test capability of ARDU is a vital complement to the wind tunnel simulation and mathematical modelling capabilities of the Laboratories. Wind tunnel tests and mathematical model results are necessary to reduce the risk in potentially hazardous flight tests and to reduce the amount of expensive flight test time required. On the other hand flight tests are necessary to validate mathematical models and wind tunnel results. The test pilots, ground crew, civilian instrumentation and aerodynamic specialists, and instrumented aircraft available at ARDU form a national facility of similar importance to major wind tunnels and computers.

5. WIND TUNNELS IN FUTURE

5.1 Low Speed

The present ARL Low Speed Tunnel, despite its deficiencies, has adequately met the Laboratories' low speed testing requirements up to the present time. However the tests currently planned for the Australian Aircraft Consortium in support of the RAAF basic trainer design could occupy the tunnel for about two years. Although this situation is marginally acceptable for a single non-recurring project, it is completely unacceptable if there is a continuing Australian aircraft design and development effort. Even if all possible productivity increasing modifications were carried out, the existing tunnel would be unable to adequately support an active aircraft industry and carry out the other low speed testing commitments of the Laboratories.

As pointed out in Ref. 3 and 13, Australia is likely to make increasing use of rotary wing and fixed wing VSTOL aircraft. These aircraft in their high lift, low forward speed operation pose unique testing problems which can currently be overcome only by the use of very large test section sizes. Overseas experience has indicated that a test section area of about $25m^2$ is the minimum required for realistic testing and the ARL Low Speed Tunnel, with a test section area of less than $6m^2$, is obviously quite unsuitable. In any new tunnel intended for VSTOL testing the provision of a ventilated test section which could be varied from fully closed through partially open to open jet conditions would have major advantages for interference assessment and reduction. The provision of a moving floor would be advantageous for low altitude ground effect tests.

If, as seems likely, the local aircraft industry continues to rely on the R&D Laboratories facilities for its aerodynamic testing requirements there are attractions to incorporating a VSTOL test capability and a conventional low speed capability in the same wind tunnel. The projected VSTOL testing requirements would not fully occupy a new facility and the remainder of the available testing time could be used to relieve the existing tunnel from the programming restraints imposed by high priority development work for industry. Development tests in support of design projects are difficult to incorporate in the work program of a single multi-purpose facility because they have rigid time requirements. These produce a very variable workload which severely disrupts the continuity of other work. The greater flexibility provided by two low speed tunnels would relieve this problem.

A tentative specification for a new tunnel to meet Australian low speed requirements is:

Tunnel type:	Continuous flow closed circuit, atmospheric pressure
VSTOL test section:	6 m x 6 m slotted walls, max test speed 60 m/sec.
High speed test section:	4.7 m x 3.4 m solid walls, max test speed 135 m/sec.
Estimated drive power:	7 MW.

A detailed presentation of this proposal is included in Reference 13.

The detail design of a new low speed tunnel including the selection between interchangeable and tandem test sections would best be done by experienced wind tunnel design consultants.

5.2 High subsonic and transonic

In the high subsonic and transonic speed ranges the ARL Transonic Tunnel and the WSRL Subsonic-Supersonic Tunnel suffer from identical problems. The maximum test Reynolds number capability of these facilities is typically a factor of 20 below flight values for current missiles and 100 below flight values for fighter aircraft in the Australian inventory. This Reynolds number gap makes extrapolation from test to flight conditions difficult and uncertain. For some cases of great practical importance, such as the operation of fighter aircraft near the buffet boundary at transonic speed, extrapolation from tunnel to flight is impossible since the low and high Reynolds number flowfields are completely different.

The second problem is that the small test section size of these facilities requires the use of very small models which are difficult to manufacture to the required accuracy, difficult to equip with adjustable control surfaces and impossible to fit with remotely controlled control surface actuators. These factors increase testing costs and seriously restrict tunnel productivity. In many cases it is necessary to test models which are larger than would be desired from tunnel interference considerations, and data accuracy and confidence levels suffer. To summarise, Australia's aerodynamic testing capability in the high subsonic and transonic speed ranges is inadequate to support the design or operation of current aircraft and missiles. At the present time the Reynolds number sensitivity of new designs is increasing and this trend will probably accelerate with the construction of very high Reynolds number wind tunnels in the USA[9] and Europe[10]. This situation arises because the aerodynamic design of aircraft has for many years been constrained by what could be tested in existing tunnels rather than by what would probably perform best in flight.

The minimum test Reynolds number required to permit confident extrapolation to flight is a difficult figure to estimate since it is strongly design dependent. A 1971 paper (Ref 7) suggested that about one quarter of full scale was an absolute minimum and nothing that has happened in the last decade reduces this estimate. A test Reynolds number capability about 25 times that currently available would therefore appear to be required for testing combat aircraft models. A facility with this capability would also be suitable for missile and stores release testing. Studies of both existing transonic tunnels[11,14] show that they cannot be modified to even approach the required Reynolds number.

The selection of a suitable size and type of high subsonic and transonic tunnel that should be constructed to meet current and future needs is very difficult. The selection process inevitably involves putting a dollar value on various capabilities and selecting the most cost effective approach to meeting our perceived needs. Operating costs over the three decades or more life of the new facility will not be insignificant and should be included in any comparisons between proposals. The operating costs that should be considered include staffing, power, tunnel maintenance and model making. A guide to tunnel size and operating pressure can be obtained from the following considerations: It has been suggested[15] that tunnel cost is directly proportional to $P^{0.8} L^{2.6}$ where P=operating pressure and L = linear scale. Since test Reynolds number is directly proportional to PL it is evident that the most economical path to high Reynolds numbers is high operating pressure and small linear scale. However Reference 8 suggests that from model and balance strength considerations 400 kPa should be regarded as the maximum practical operating pressure at transonic speeds for combat aircraft testing. Even at this pressure it may not be possible to equip models with movable control surfaces, and supporting sting diameters will be approaching the model rear fuselage diameter. At subsonic speeds, for the same model stresses, the operating pressure may be increased in inverse proportion to the square root of the Mach number. If a transonic operating pressure limit of 400 kPa is accepted, a test section size of about 2 m square is required to obtain the desired minimum test Reynolds number (1/4 of full scale) on current combat aircraft. This test section size is also attractive because models of the scale required can be conveniently manufactured on current numerically controlled machines and entry to the test section for model adjustments is relatively easy due to the full standing headroom

In most high subsonic and transonic wind tunnel designs it is possible to provide a low speed ($0.2 < M < 0.5$) testing capability without significantly increasing the cost or compromising the high speed performance. Such a low speed capability would be very valuable, since the same models used for high speed tests could be employed, and its inclusion is recommended. It should be noted that this low speed capability would be quite unsuitable for VSTOL or traditional aircraft development testing.

Any new high subsonic-transonic tunnel constructed should have a maximum Mach number of at least 1.4 to avoid a gap in available test data between the highest transonic Mach number tests and the lowest supersonic tests.

In some types of transonic tunnel it is possible to provide a test capability for Mach numbers above 1.4 without compromising the overall design or greatly increasing the facility cost. The possibility of obtaining a bonus supersonic capability should be seriously considered since the current projected supersonic workload barely justifies a dedicated facility.

An outline specification of a new transonic tunnel to meet Australian requirements becomes:

Working section:	2 m square.
Maximum stagnation pressure:	400 kPa at transonic speeds
Basic Mach number range:	0.5 to 1.4
Extended subsonic capability:	Mach number range 0.2 to 0.5
Extended supersonic capability:	Mach number range 1.4 to 3 (see next section for more details)

There are a number of tunnel types[11] which could meet the above specifications and the final selection will almost certainly require assistance from experienced wind tunnel design consultants.

Preliminary investigations carried out at ARL and WSRL indicate that the choice will probably be between an intermittent blowdown tunnel and a continuous closed circuit compressor driven facility. Both tunnel types can meet the basic specification and provide some of the desired extended subsonic and supersonic test capability. The blowdown tunnel provides the subsonic capability with no changes to the basic transonic design and the supersonic capability is obtained simply by extending the operating range of the flexible nozzle which is located upstream of the test section. To effectively operate a continuous transonic tunnel at low subsonic speed it would be necessary to incorporate variable pitch blading in the compressor and possibly a multi-ratio gearbox in the compressor drive. A modest supersonic capability could be provided in a separate circuit by using the plenum chamber auxiliary suction compressor plant, required for transonic operation, as a drive for a continuous supersonic tunnel with a test section size about one quarter that of the main tunnel.

The decision between the two tunnel types is a complex one which, as noted previously, could best be made with assistance from consultants. Some of the major factors to be considered are briefly outlined below.

A typical blowdown tunnel of the size under consideration[16] has a run time of about 10 sec at its maximum Reynolds number, rising to about 60 sec at its minimum operating Reynolds number. The continuous tunnel has an effectively unlimited run time. It appears that virtually all of the types of testing which can be carried out in a continuous tunnel can also be carried out in a blowdown one. The main problem identified to date is aircraft-store interaction testing using an auxiliary model support system. Few of the world's blowdown transonic tunnels are equipped with such a system and a significant design and development effort would be required to produce this capability. This area warrants serious study, since store release testing will form a major part of the projected transonic tunnel workload.

The most productive blowdown transonic tunnel in current use (NAE Canada, 5 ft x 5 ft) has a maximum operating rate of 2 runs per hour, giving a total testing time of about 12 hours per year at maximum Reynolds number for single shift operation. This short total test time compared to the virtually unlimited time available from a continuous facility necessitates a very high data production rate. High data production rates demand high flow quality, computer control of model attitude, a fast response control system for the tunnel flow conditions and a fast data acquisition system. Present indications based on overseas experience are that a blowdown tunnel could meet current and projected transonic test requirements without resorting to multi-shift operation.

A blowdown tunnel is inherently very inefficient in its use of energy. For equal Reynolds number, test section size and wind-on test time a blowdown tunnel will consume about 10 times as much energy as a continuous compressor driven tunnel. However, if an electric motor drive is used, this energy ratio is not necessarily reflected in an equivalent operating cost ratio. The nearly continuous 5 to 10 MW load required to drive the recharging compressors of a blowdown tunnel is a much more acceptable proposition for electricity supply authorities than the intermittent 50 MW load presented by a continuous compressor driven facility. Enquiries to Australian electricity supply authorities indicate that the tariff charged for an intermittent 50 MW load would have to be decided by negotiation and would definitely reduce, and possibly even negate, the apparent operating cost advantage of the continuous tunnel. Other drive arrangements such as gas fired turbines, which are known to exist in the 50 MW class, may provide a practical alternative to an electric drive for a large continuous tunnel.

An atmospheric exhaust blowdown tunnel has a potential problem with the high minimum stagnation pressure required for starting at high supersonic Mach numbers. At a Mach number of 4 the minimum stagnation pressure is about 800 kPa and the resulting very high model loads may create excessive stresses in structurally complex models. Continuous closed circuit tunnels can operate at stagnation pressures well below atmospheric and model loading problems should be minimal.

All the above observations have been based on the use of an ambient temperature tunnel with air as the working fluid. It is considered that cryogenic nitrogen tunnels of the type existing and proposed in a number of countries for very high Reynolds number testing are not appropriate for a general purpose facility of our proposed Reynolds number. The absence of an established technology base overseas and in Australia would make the design, construction and operation of a cryogenic tunnel a very expensive and technically risky undertaking. Nevertheless, in any new facility design, the possibility of future cryogenic operation should be considered since this would be one path to extending local testing capabilities if new requirements arose early in the next century.

5.3 Supersonic

There are two distinct requirements in the supersonic speed range; aircraft tests, including stores carriage and release, and missile tests. For aircraft investigations, the relevant Mach number range is 1.4 to 2.0 where the lower limit is the minimum interference free Mach number that can be achieved with solid walls and the upper limit is the maximum flight Mach number of aircraft likely to be in Australian service in the next three decades. The Mach number range up to 1.4 is conveniently covered by most transonic wind tunnels. It is recognised[3] that current Australian interest in supersonic operation is limited. Nevertheless there are clear indications that supersonic missile carriage and release and combat could become important in the coming decades. Due to their small test section size and their limited Reynolds number capability the existing supersonic tunnels S-1 and S-3 do not provide a satisfactory supersonic aircraft testing capability.

For missile aerodynamic research and development the maximum Mach number of interest extends to at least 3. It is considered that the existing tunnels provide a minimal test capability for relatively simple weapon configurations. However they are not adequate for testing more advanced designs typical of modern precision guided munitions.

Model load considerations, particularly for aircraft store interaction experiments, suggest that stagnation pressures in the Mach number range from 1.4 to 2.0 should not exceed 200 kPa. Model making and handling criteria indicate that the span of an aircraft model should lie between 0.5 m and 1 m. For this range of model size a test section about 1.5 m square is appropriate. Operation of a tunnel of this size at a Mach number of 1.4, stagnation pressure of 200 kPa and stagnation temperature of 20°C gives a Reynolds number of 45 million per metre. The Reynolds number based on mean chord of a 1/16th scale F/A-18 model is about 8 million, representing about one quarter of the flight Reynolds number at M=1.4. This is considered to be an acceptable level of simulation for a wide range of conditions. A 1.5 m tunnel with a Reynolds number capability of 45 million per metre at M=1.4 provides an adequate capability for missile aerodynamic testing. The stagnation pressure would need to be increased to 400 kPa to maintain a Reynolds number of 45 million per metre at a Mach number of 3.

The almost intractable problems of carrying out aircraft-store interaction work in a tunnel as small as S-1 (0.38 m square working section) have been described. It is important that any new tunnel should have the capacity for this type of experiment. A 1.5 m square working section is about the minimum size that would accommodate an appropriate scale of test hardware without causing severe and possibly insoluble blockage problems. The above arguments lead to the specification of a supersonic tunnel with the following characteristics:

Mach number range:	1.4 to 3.0
Stagnation pressure range:	150 to 400 kPa
Working section	1.5 m square

For a dedicated supersonic facility, considering the projected workload, the only feasible and economical technical solution to meet the specification is an intermittent blowdown tunnel. There are many examples of tunnels with similar specifications operating in the world today, and so the design, manufacture and installation of such a tunnel does not involve high technical risk. A blowdown tunnel of the size proposed normally operates with atmospheric exhaust. As a result, the stagnation pressure and Reynolds number ranges are limited, and model loads are large. The relatively short running time (10 to 60 sec) of such a tunnel is an experimental inconvenience. Nevertheless, such a tunnel meets the requirements, and its productivity would seem to be adequate to meet foreseeable test demands.

A blowdown transonic tunnel meeting the requirements given in the previous section could easily be made to meet the above specification. A continuous supersonic tunnel driven by the auxiliary suction plant of a continuous transonic tunnel would provide a reduced Reynolds number capability in the required Mach number range.

To summarise: the existing Australian supersonic tunnels are inadequate for both aircraft and all but a limited range of missile testing. The most cost-effective new facility to meet current and projected future supersonic requirements is a blowdown tunnel with a test section about 1.5 m square. If a new blowdown transonic tunnel were constructed, it could also fulfil the supersonic requirements for very little additional cost. If a new continuous transonic tunnel were constructed, the supersonic requirements could be partly met by an auxiliary tunnel powered by the plenum chamber suction plant of the main tunnel.

5.4 Location of Future Facilities

For completeness some notes on the factors to be considered when selecting a site for future aerodynamics test facilities will be included.

If a single new facility is planned with little possibility of others being built in the foreseeable future, it should be co-located with one of the existing groups of wind tunnels (ARL or DRCS). In this way expensive support facilities such as libraries, model making workshops and major computer installations would not have to be duplicated. The cost of providing these necessary facilities on a new site would be a significant proportion of the total cost of a wind tunnel.

If a number of new facilities were planned for simultaneous or consecutive construction, there are strong arguments for establishing a new laboratory. The support requirements for a group of new facilities would overload either of the existing laboratories and the costs of establishing new supporting capabilities would not be unreasonable since they would be shared between the tunnels. For a new laboratory, reasonable proximity to a large city appears to be essential because of the need to have quick and easy access to a large industrial and technological base. This point was also noted by ASTEC in its report[1].

6. FLIGHT TEST FACILITIES IN FUTURE

6.1 Aircraft flight testing

It has been suggested[2] that the R&D Laboratories should establish and maintain an independent aircraft flight test capability. While this is very attractive from the point of view of access to aircraft for flight research, it would be costly for the Laboratories and difficult to implement when Service aircraft were required. On balance it is considered that the Laboratories should continue to use the RAAF Aircraft Research and Development Unit (ARDU). It has been pointed out previously that wind tunnel testing and flight testing enjoy a complementary relationship. The accuracy and safety of these activities are mutually interdependent.

It is inappropriate for us to write on the upgrading of ARDU's facilities. However, the Laboratories will need adequate access to instrumented aircraft in future to perform their role. With this in mind we believe that at least one or possibly two aircraft of each new type purchased should be wired by the manufacturer for flight testing instrumentation. We understand that this is the case in the F/A-18 aircraft purchase. This should eliminate much of the delay that has occurred between the introduction into service of the F-111C aircraft in Australia and the completion of the instrumentation installations. Upgrading of computer facilities for reading instrumentation tapes and data analysis will be necessary.

6.2 Gas gun launched vehicle testing

The gas-gun launched vehicle technique provides an important aerodynamic test facility interposed between the wind tunnel and full scale flight testing. It has a particular role in validation of predicted aerodynamic behaviour and for ad hoc tests to assess flight behaviour and the effect of design changes. The existing subsonic gas guns are adequate to meet requirements for the foreseeable future, and the transonic gun will provide a much-needed high speed capability.

Some flight testing of instrumented projectiles is carried out using full-scale shells fired from guns operated by the Army at Port Wakefield, S.A. To obtain high quality aerodynamic data from such firings, it is necessary to determine accurately the trajectory of the shell over long ranges. To achieve this, a precision tracking radar is needed; this is the only major item needed to upgrade the present facilities.

6.3 Rocket launched vehicle testing

The retention of the Woomera Range and its upgrading cannot be justified on the basis of defence R&D needs in aerodynamics alone. Range requirements need to be considered in the context of total defence requirements. It should be able to cope not only with the testing of the foreseeable types of weapons systems but also with the initial development and validation work that the Laboratories must continue to do if they are to fulfil their R&D role in support of the Defence Force.

Aerodynamic development and validation of prototype air-to-air and air-to-ground weapons require that instrumented flight vehicles be either dropped from an aircraft or boosted to an appropriate altitude using the rocket launch technique. The use of aircraft for ab initio development entails extensive qualification and clearance work to ensure that the aircrew and aircraft are not endangered. In such circumstances, the rocket launch technique may represent a useful and economic alternative to the use of an aircraft, particularly in the exploratory phases of the development program. To be useful, a range needs to be adequately instrumented with modern radar and optical tracking facilities, telemetry receiving facilities and adequate data handling facilities to provide real-time tracking and data displays. A range should be manned at a level to provide a competent and efficient range authority role and in a manner that provides adequate maintenance and efficiency levels.

To upgrade and maintain the Woomera range to the necessary standard would require a substantial initial expenditure and a continuing commitment of resources. As this would run counter to the present policy of reduced expenditure on the Range, upgrading would need to be linked to future Defence Force proposals such as the establishment of an air combat manoeuvring range by the RAAF.

7. SUMMARY AND RECOMMENDATIONS

The case has been made that Australia's wind tunnel testing capability in the subsonic, transonic and supersonic speed ranges is inadequate. The most reliable current estimate is that the rapidly expanding field of computational aerodynamics will not significantly reduce the need for wind tunnel testing in the foreseeable future. Other aerodynamic data production options such as greatly increased flight testing or buying time in overseas facilities are not considered to be satisfactory or cost effective alternatives. It is therefore an appropriate time to establish what new facilities are required to meet Australia's aerodynamic data needs into the next century.

The transonic speed range is the one in which current deficiencies are most serious. It is no longer possible to produce reliable data over a significant and important part of the flight envelope of current Service aircraft. This seriously impairs our capability to mathematically model the behaviour of current and future aircraft. In particular the low Reynolds number capability and small test section size of the existing transonic facilities render them unsuitable for most types of tests on the recently purchased F/A-18 fighter. In future, the modelling and assessment of precision-guided and unguided weapons will be degraded if a new transonic facility is not built. Store carriage and release testing, which is mostly carried out in the high subsonic and transonic speed range, involves uncertainties due to facility limitations. Errors in store release test data can have catastrophic consequences during test or operational flying.

In our view a new transonic facility is the first priority, since existing tunnels cannot be upgraded to the required standard. The broad specification of a suitable new transonic facility is:

Test section:	2 m square
Maximum stagnation pressure:	400 kPa
Mach number Range:	0.5 to 1.4

The final decision on the type of tunnel which best meets our needs will require assistance from experienced wind tunnel design consultants. Preliminary considerations suggest that the choice will be between a continuous closed circuit compressor driven tunnel and an intermittent blowdown tunnel. The major drawbacks of a continuous facility are higher initial cost and very high peak power demand; for a blowdown tunnel the major problems are the short individual run duration and a much lower available total testing time.

In both blowdown and continuous transonic tunnels it is possible to provide an extended subsonic and supersonic test capability without compromising the transonic performance or greatly increasing th total facility cost. The desirable extended capabilities which may be possible are:

Subsonic:	Mach number range 0.2 to 0.5 in the transonic test section with a maximum stagnation pressure of at least 400 kPa.
Supersonic:	Mach number range 1.4 to 3 preferably in the transonic test section, but possibly in a smaller auxiliary test section, with a maximum stagnation pressure of 400 kPa.

We consider that these extended capabilities would greatly increase the value of a new facility and we recommend their inclusion in the design requirements for any new transonic tunnel.

In the supersonic speed range the present S-1 tunnel is inadequate in both Reynolds number capability and test section size for testing full models of military aircraft in the relevant Mach number range of 1.4 to 2.0. Fortunately up to the present time, the demand for supersonic aircraft testing has been small. However, if as seems quite possible, aircraft with a real supersonic cruise, combat and missile delivery capability are developed and acquired by Australia, adequate supersonic testing capabilities will be required to support their operation. The S-1 and S-3 tunnels have a minimum capability for testing missiles with simple shapes but are inadequate for testing configurations typical of modern guided weapons. As for aircraft testing the deficiencies are in the areas of Reynolds number capability and test section size.

It has been suggested that local defence industries are more likely to undertake weapon design programs than more expensive aircraft design projects. Many current and proposed weapon systems involve supersonic projectiles and a prerequisite to local development programs would be the existence of adequate supersonic test facilities.

An outline specification of a new supersonic tunnel to meet Australian requirements is:

Type:	Intermittent blowdown
Test section:	1.5 m square
Mach number range:	1.4 to 3
Stagnation pressure range:	150 to 400 kPa.

It is our view that, while the deficiencies in existing supersonic facilities are clearly evident, the provision of a new supersonic tunnel has a lower priority than that of the new transonic tunnel discussed previously. It is probable that the supersonic capability of a new transonic tunnel could meet most, if not all, our projected supersonic testing requirements. If this dual use of a single new tunnel were adopted, particular attention would have to be paid to the productivity of the facility.

In comparison to the transonic and supersonic speed ranges, the situation in the low speed area is less clear. It is evident that the existing low speed tunnel has capabilities which are deficient for many of the tests carried out in it and that it has no capability for VSTOL testing in the low speed high lift regime. However there is a wide divergence of opinion about the relative importance of the various test capabilities which could be provided by a new low speed tunnel. The situation is made less clear by the current uncertainty regarding the introduction of VSTOL combat aircraft into the Australian inventory and the fact that much of the work done in the existing tunnel is for the aircraft industry who have not yet formally stated their requirements.

In our view there is a need for improved low speed testing capabilities and this need ranks in importance with the provision of a new supersonic tunnel. However, this priority would be significantly increased if a clear requirement to support VSTOL aircraft operations developed. We consider that the specification of any new low speed facility should await the outcome of the forthcoming workshop where industry will have an opportunity to express its requirements.

A review of low speed testing needs from an ARL viewpoint and one proposal to meet these needs is presented in Reference 13.

In contrast to the wind tunnel situation, Australia's flight testing facilities are adequate in areas other than the Woomera Range. The RAAF Aircraft Research and Development Unit provides a vital aircraft flight test service and it is essential that this capability be maintained and the R&D Laboratories continue to have access to it. The gas gun launched vehicle test ranges at DRCS provide a very useful test capability which would be significantly upgraded by the provision of a precision tracking radar.

In the past the Woomera Range has provided a useful rocket launched vehicle test capability. Unfortunately defence R&D needs in aerodynamics by themselves are not sufficient justification for the retention and upgrading of the Range. However if it were decided to revitalise the Range for other purposes it would continue to provide a most useful flight test capability.

8. CONCLUDING REMARKS

It is instructive to consider the contribution that the present wind tunnels have made to Australian aeronautics over their 25 to 40 year life. Without these tunnels the Jindivik, Winjeel and Nomad aircraft, the Malkara, Ikara and Turana missiles, the Karinga bomb and the Tonic towed target could not have been designed and built and the current RAAF basic trainer project would have been impossible. In addition a similar number of projects which did not reach production, but which were invaluable exercises for local designers, could not have been undertaken.

At various times the majority of combat aircraft that have been in local service have been tested in the tunnels. These tests have encompassed ad hoc problem solving, assessment of local modifications, clearance of store carriage and release and the production of data banks for mathematical modelling.

The research work which has been carried out in these tunnels has generated a large number of scientific and technical papers which have obtained a respected place for Australia in the world aerodynamic community. This international recognition has had considerable practical value in gaining access to overseas results which might otherwise have been denied us. Australia's current participation in a number of TTCP panels is directly or indirectly facilitated by our possession of (just) credible tunnel facilities.

The above notes are not intended to be a comprehensive list of work carried out in the tunnels but rather to indicate the sort of advantages that result from tunnel ownership. It is difficult to do a retrospective cost effectiveness study for a facility like a wind tunnel but it seems abundantly clear, at least to the authors, that the investment in the existing tunnels has been repaid many times. There is no apparent reason why new tunnels built now will not similarly repay the initial investment with interest over their three to four decade operating life.

A further basic point which should be mentioned is the danger of justifying a wind tunnel purely on the present workload. Wind tunnels, like computers, and other large technical tools, promote a workload which is dependent on their capabilities. A capable wind tunnel facility manned by competent, enthusiastic staff would achieve a high level of productivity unattainable by existing facilities. Therefore, it is strongly suggested that projected requirements and not current utilisation should be used when considering new tunnel facilities. This point is particularly important when some of the existing test capabilities are so grossly deficient.

In conclusion, the tunnels which were constructed in the 1940s and 50s and which have given invaluable service over the years are no longer adequate for current and future needs. It is now time for a commitment to the next thirty years of aeronautics in Australia, similar to the one made by the farsighted planners of our existing wind tunnels.

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16. Abstract

Existing Australian aerodynamic test facilities are reviewed with respect to their suitability to meet current and projected Defence needs. The deficiencies of the existing facilities are identified and new facilities proposed.

This document is a compilation of views of the authors and of senior staff engaged in the management and practice of aerodynamics at the Aeronautical Research Laboratories and the Weapons Systems Research Laboratory.

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